US009153408B2

(12) **United States Patent**
Neuser et al.

(10) **Patent No.: US 9,153,408 B2**
(45) **Date of Patent: Oct. 6, 2015**

(54) **MICROFOCUS X-RAY TUBE FOR A HIGH-RESOLUTION X-RAY APPARATUS**

(75) Inventors: **Eberhard Neuser**, Wunstorf (DE); **Andreas Schmitt**, Wunstorf (DE); **Wolfgang Johannes Sperner**, Wunstorf (DE)

(73) Assignee: **GE Sensing & Inspection Technologies GmbH**, Hurth (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 320 days.

(21) Appl. No.: **13/818,994**

(22) PCT Filed: **Aug. 27, 2010**

(86) PCT No.: **PCT/EP2010/005273**
§ 371 (c)(1),
(2), (4) Date: **Apr. 22, 2013**

(87) PCT Pub. No.: **WO2012/025136**
PCT Pub. Date: **Mar. 1, 2012**

(65) **Prior Publication Data**

US 2013/0208870 A1 Aug. 15, 2013

(51) **Int. Cl.**
H01J 35/12 (2006.01)
H01J 35/14 (2006.01)
H01J 35/10 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01J 35/12*** (2013.01); ***H01J 35/105*** (2013.01); ***H01J 35/14*** (2013.01); ***H01J 35/16*** (2013.01); ***H05G 1/025*** (2013.01); *H01J 2235/087* (2013.01); *H01J 2235/12* (2013.01); *H01J 2235/1216* (2013.01); *H01J 2235/1262* (2013.01); *H01J 2235/1266* (2013.01)

(58) **Field of Classification Search**
CPC H01J 35/105; H01J 35/12; H01J 35/14; H01J 35/16; H01J 2235/087; H01J 2235/12; H01J 2235/1216; H01J 2235/1262; H01J 2235/1266
USPC 378/130, 137, 138, 141, 199, 200
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,917,099 A 7/1933 Coolidge
2,356,645 A 8/1944 Atlee

(Continued)

FOREIGN PATENT DOCUMENTS

CN 1910968 A 2/2007
CN 101026077 A 8/2007

(Continued)

OTHER PUBLICATIONS

Unofficial English translation of JP Office Action issued Apr. 1, 2014 in connection with corresponding JP Patent Application No. 2013-525146.

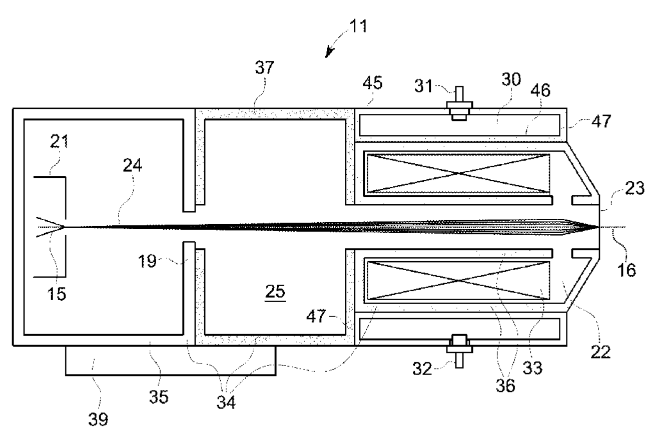
(Continued)

Primary Examiner — Allen C. Ho
(74) *Attorney, Agent, or Firm* — GE Global Patent Operation; Douglas D. Zhang

(57) **ABSTRACT**

An apparatus is provided for a micro focus X-ray tube for a high-resolution X-ray including a housing, an electron beam source for generating an electron beam and a focusing lens for focusing the electron beam on a target. The micro focus X-ray tube includes a substantially rotationally symmetrical, ring-shaped cooling chamber configured to circulate a liquid cooling medium.

11 Claims, 4 Drawing Sheets



(51) **Int. Cl.**
H01J 35/16 (2006.01)
H05G 1/02 (2006.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,608,664	A	9/1945	Buechner	
6,249,569	B1 *	6/2001	Price et al.	378/130
6,430,263	B1	8/2002	Lu	
6,438,207	B1 *	8/2002	Chidester et al.	378/138
6,580,780	B1 *	6/2003	Miller	378/141
6,852,982	B1	2/2005	Bierhoff et al.	
6,977,991	B1 *	12/2005	Neumeier et al.	378/141
7,025,502	B2 *	4/2006	Freudenberger et al.	378/200
7,197,118	B2 *	3/2007	Anno et al.	378/130
7,443,957	B2 *	10/2008	Freudenberger et al.	378/130
7,499,525	B2 *	3/2009	Horndler et al.	378/130
7,508,916	B2 *	3/2009	Frontera et al.	378/130
7,515,687	B2	4/2009	Bernard et al.	
7,520,672	B2 *	4/2009	Thangamani et al.	378/199
7,522,706	B2	4/2009	Lu et al.	
7,558,376	B2 *	7/2009	Anno	378/130
7,580,507	B2 *	8/2009	Lu et al.	378/141
8,009,805	B2 *	8/2011	Smith et al.	378/130
8,009,806	B2 *	8/2011	Legall	378/132
2007/0230662	A1 *	10/2007	Imai et al.	378/130
2009/0225951	A1 *	9/2009	Wandke et al.	378/141
2010/0046715	A1 *	2/2010	Freudenberger	378/140

FOREIGN PATENT DOCUMENTS

EP	1970935		9/2008
GB	235892		11/1925
JP	03152844	A	6/1991
JP	2001006592	A	1/2001
JP	2004055262	A	2/2004
JP	2004079304	A	3/2004
JP	2005038857	A	2/2005
JP	2006128137	A	5/2006
JP	2009123555	A	6/2009

OTHER PUBLICATIONS

PCT Search Report and Written Opinion from corresponding PCT Application No. PCT/EP2010/005273, Dated May 20, 2011.
Translation of CN office Action issued on Feb. 28, 2015 in relation to corresponding CN application 201080068842.0.
Unofficial English translation of Notice of Allowance issued in connection with corresponding JP Application No. 2013-525146 on Dec. 1, 2014.

* cited by examiner

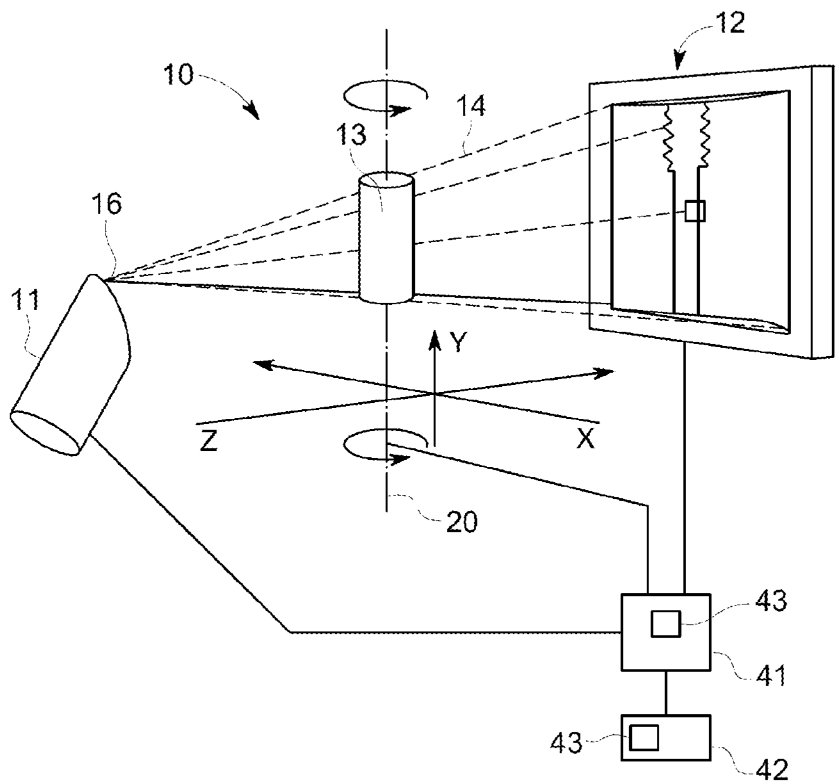


FIG. 1

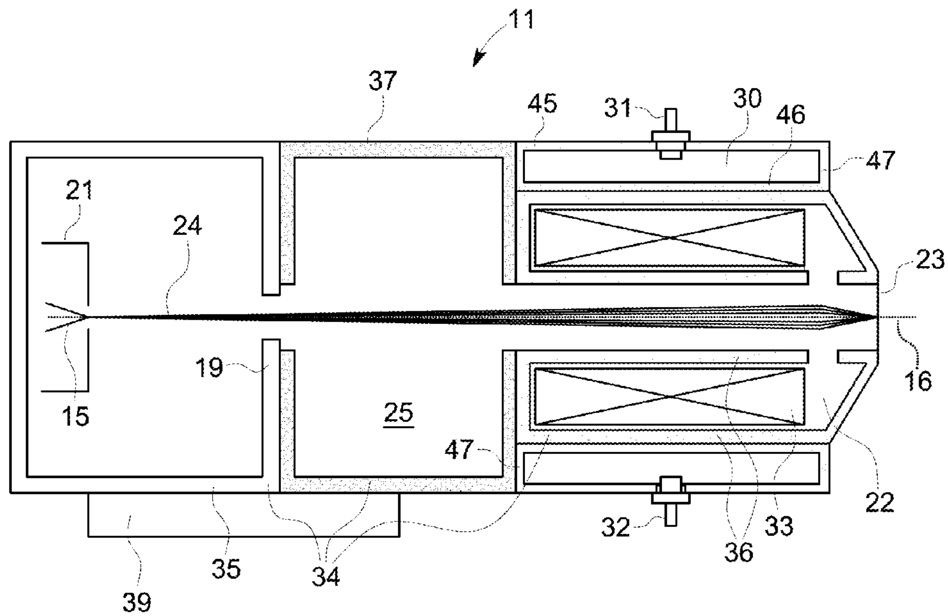

11
37
45
31
30
46
47
21
24
23
19
16
15
25
47
22
32
33
36
35
34
39

FIG. 2

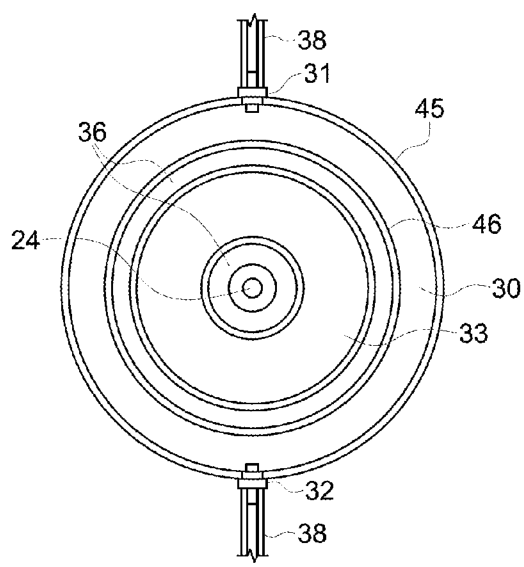

38
31
45
36
46
24
30
33
32
38

FIG. 3

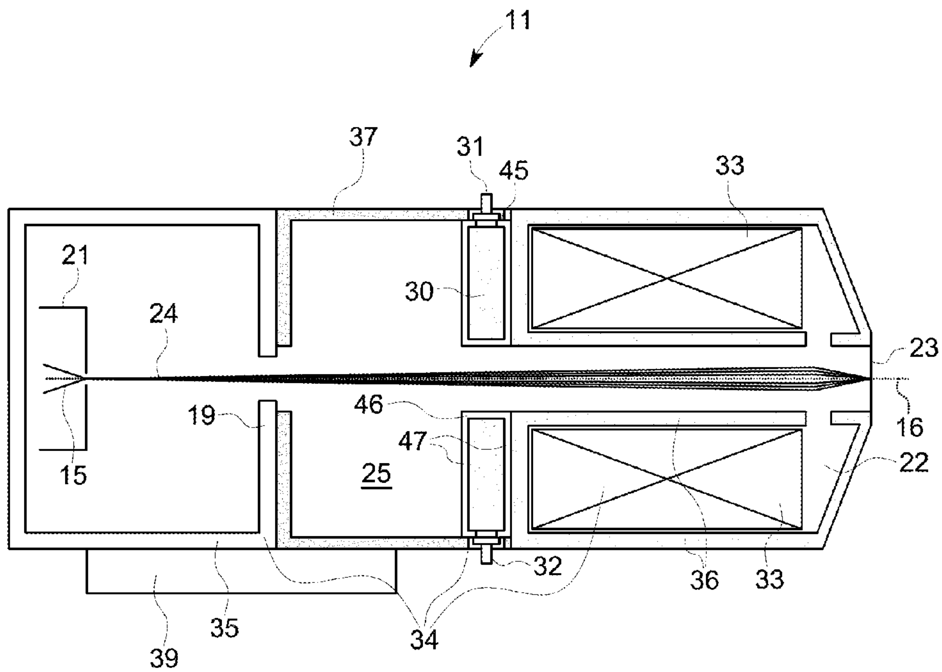


FIG. 4

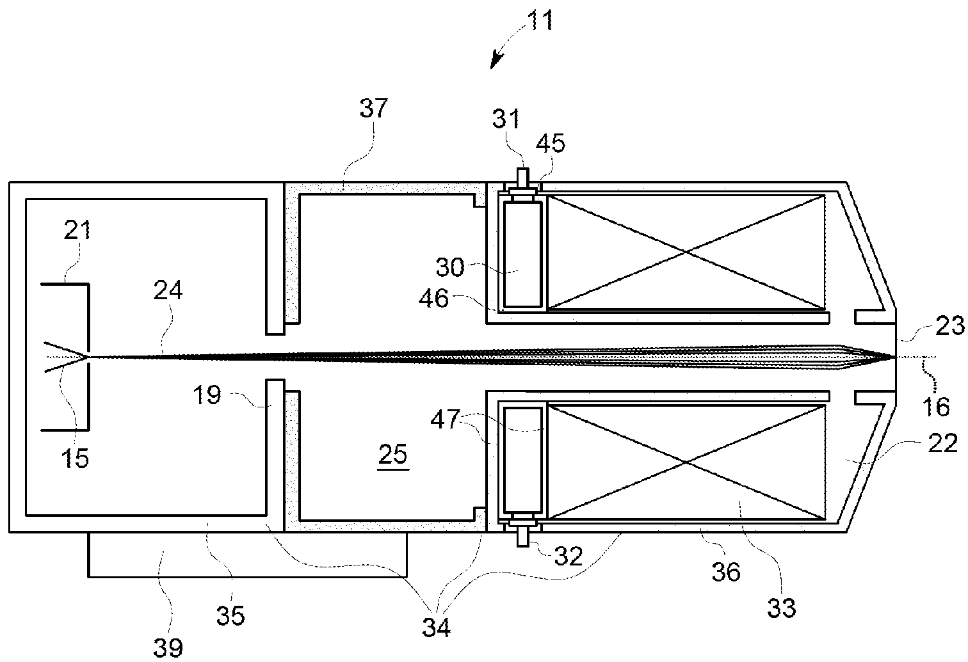

11
37
31
45
21
30
24
46
23
16
19
47
25
22
15
32
36
35
34
33
39

FIG. 5

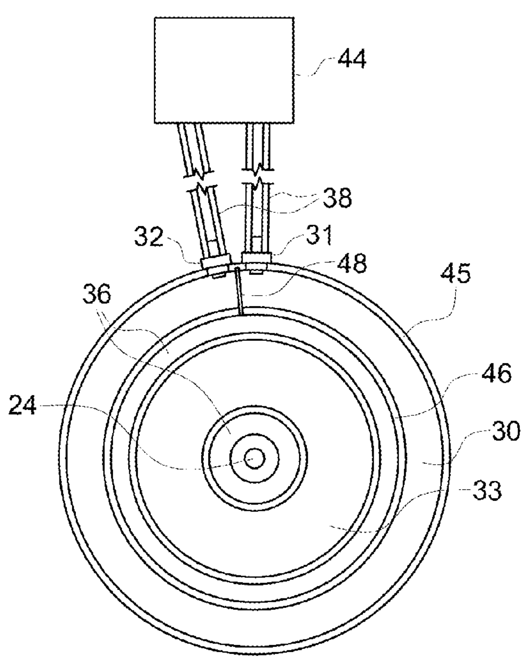

44
38
32
31
48
45
36
46
24
30
33

FIG. 6

MICROFOCUS X-RAY TUBE FOR A HIGH-RESOLUTION X-RAY APPARATUS

This is a national stage application under 35 U.S.C. §371 (c) of prior-filed, co-pending PCT patent application serial number PCT/EP2010/005273, filed on Aug. 27, 2010, the entire contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Embodiments of the present invention relate to a micro focus X-ray tube for a high-resolution X-ray device comprising a housing, an electron beam source for generating an electron beam, and a focusing lens for focusing the electron beam onto a target. Such X-ray tubes are known, for example, for high-resolution computer tomography devices.

Due to advances in detector technology, in computing and in storage capacities as well as the increased resolution of micro focus X-ray tubes, the micro-CT allows the volume reconstruction with a very high spatial resolution (voxel size) up to the sub-micrometer range.

Since the measurement of all the X-ray projections, which are required for a reconstruction with high resolution, takes several hours typically, thermally induced displacements of the sample projections create significant problems on the detector. Although it is known that these displacements are compensated using software-based algorithms, the resolution improvement thus achieved is limited.

The critical component is the X-ray tube, because it is not possible to fix the tube in the focal spot on a thermally insensitive manipulator; it always remains a thermo sensitive (usually metallic) connection over the tubular housing between the focus and the attachment of the tube on the manipulator, which, without further measures leads to the fact that the focus position of the X-ray tube over the duration of measurement moves considerably.

A common measure, to keep the focus position of the x-ray tube over the entire measurement period as constant as possible, consists of heating up the tube to operating temperature and waiting until a thermal equilibrium is reached before the scans are started. However, it takes several hours until the thermal equilibrium is reached because of the considerable mass of the X-ray tube and the associated large heat capacity. Furthermore, the thermal equilibrium is disturbed again with each parameter change of the tube, causing additional significant delays.

The objective of the embodiments of the invention is to provide a micro-focus X-ray tube which allows, in the industrial application, to obtain data in a shorter time with a higher resolution.

BRIEF DESCRIPTION OF THE INVENTION

Provided is a micro focus X-ray tube for a high resolution X-ray apparatus, the X-ray tube comprising a housing, an electron beam source for generating an electron beam and a focusing lens for focusing the electron beam on a target, wherein the X-ray tube comprises a substantially rotationally symmetrical, ring-shaped cooling chamber configured to circulate a liquid cooling medium.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are explained below on the basis of advantageous embodiments with reference to the following accompanying drawings:

FIG. **1** is a schematic representation of a micro-computer tomography system;

FIG. **2** is a schematic representation of a micro-focus X-ray tube.

FIG. **3** is a cross section through an X-ray tube perpendicular to the longitudinal axis;

FIG. **4** is a longitudinal cross section through an X-ray tube in an embodiment;

FIG. **5** is a longitudinal cross section through an X-ray tube in an embodiment; and

FIG. **6** is a cross section through an X-ray tube perpendicular to the longitudinal axis, in an alternative embodiment to FIG. **3**.

DETAILED DESCRIPTION OF THE INVENTION

As shown in FIG. **1**, micro computed tomography apparatus comprising an x-ray system **10**, which is adapted to receive a set of X-ray projections of a sample **13**. For this purpose, the X-ray system **10** comprises a micro focus X-ray tube **11**, the X-ray radiation **14**, emitted on basis of a focal point or focus **16** of the micro focus X-ray tube **11**, an imaging X-ray detector **12**, and a sample holder **20**, which is set up to rotate the sample **13** about a vertical axis. X-ray detector **12** is a surface detector, in particular a flat panel detector, however, a line detector is also possible. A set of x-ray projections of the sample **13**, each receives for example, a defined small angle step and recording an x-ray projection at each angle of rotation by gradually rotating the sample holder **20**. The X-ray system **10** is not limited to a rotation of the sample holder **20** about a vertical axis. Alternatively, for example, the micro focus X-ray tube **11** and the X-ray detector **12** are rotated about the stationary sample **13**.

The X-ray projections are read from the X-ray detector **12** and transmitted to a computing device **41**, where reconstructed three-dimensional volume data **43** of the sample **13** can be calculated from the set of recorded x-ray projections by means of a basically known reconstruction algorithm and, for example displayed on a screen **42**. The computing device **41**, as shown in FIG. **1**, can also be set up to control the micro focus X-ray tube **11**, the sample holder **20** and the X-ray detector **12**, alternatively, a separate control device can be provided.

The micro focus X-ray tube **11** includes a cathode element **15**, a Wehnelt cylinder **21**, an anode **19**, a focusing lens **22** designed as an electromagnetic lens and an electron beam target **23**. Furthermore, a further electromagnetic lens **25** may be provided, which is set up as a condenser lens, around the electron beam **24** approximately aligned parallel or to generate an intermediate image, and the condenser lens **25** is however not absolutely necessary. The micro focus X-ray tube **11** also expediently includes a not shown deflector for beam position adjustment. The micro focus X-ray tube **11** is arranged so that the minimum focus or focal spot on the electron beam target **23** is smaller than or equal to 10 μm.

The micro focus X-ray tube **11** further comprises a housing, which can be composed of a plurality of sections. In particular, a housing portion **35** can be provided which accommodates the cathode element **15** and forms the anode **19**, a housing portion **36** may be provided which surrounds a focusing lens **22** and, optionally, there may be an intermediate arranged middle housing portion **37**, in which, for example, the condenser lens **25** may be arranged. The coil **33** in the housing portion **36** is free of thermal insulation, in particular non-metallic screens or layers that would impede the setting of a thermal equilibrium.

The micro focus X-ray tube **11** comprises an annular cooling chamber **30**, which has an inlet **31** and an outlet **32** which are connected to a cooling circuit via coolant lines **38**, with a coolant pump **44**. In this manner, a liquid coolant, in particular water or oil, flow through the cooling chamber **30** so that the input of heat energy from a variety of internal and external heat sources and an associated displacement of the focal point **16** counteract relative to the tube mounting **39**. The mentioned heat sources arise, for example due to the impact of the electron beam **24** on the electron beam target **23**, the energy dissipation in the focusing lens **22** and the absorption of thermal energy over the surface of the tube housing **34**.

The cooling chamber **30** is closed in a ring, as best seen in FIGS. **3** and **6**. In the embodiment of FIG. **3**, the liquid flowed through the interior of the cooling chamber **30** is circumferentially completely throughout. In this embodiment, inlet **31** and outlet **32** are offset by 180° to each other, ie, oppositely arranged, as shown in FIG. **3**, so that the cooling chamber **30** is passed through as uniformly as possible and no preferential direction of flow for the cooling medium forms.

In the embodiment of FIG. **6**, however, a radial partition **48** is provided in the cooling chamber **30**, which interrupts the fluid flowed through the interior of the cooling chamber **30** at a point on the circumference. In this case the inlet **31** and outlet **32** are arranged suitably in the region of the radial partition **48** on opposite sides of the same in order to achieve a full flow through the cooling chamber **30**. In this embodiment, the inlet **31** and outlet **32** can also be essentially without circumferential offset, but instead can be arranged axially offset.

The embodiment according to FIG. **6** illustrates that the inventive feature "substantially rotationally symmetrical" means: rotationally symmetrical apart from inlets and outlets **31**, **32** for the coolant, any radial partition **48** in the cooling chamber **30**, and optionally further, the rotational symmetry not substantially interfering functional elements. The terms axial, radial and rotational symmetry refers in this application to the longitudinal axis of the micro focus X-ray tube **11**, which is defined by the central axis of the electron beam **24** between the cathode **15** and the electron beam target **23**.

In the embodiment of FIG. **2**, the cooling chamber **30** is arranged to the tube housing **34**, in particular the focusing lens **22** is disposed around the surrounding housing portion **36**. In this embodiment, the cooling chamber **30** extends substantially axially, i.e. its axial extension is approximately at least twice as large as their radial extension. For example, the axial extent of the cooling chamber **30** to the axial extent of the coil **33** of the focusing lens **22** can be adjusted.

In the embodiments of FIGS. **4** and **5**, the cooling chamber **30** is arranged in the tube housing **34**. In the variant shown in FIG. **4**, the cooling chamber **30** is arranged on the outside on the focusing lens **22** surrounding housing portion **36**, here in the middle housing portion **37**. In the variant shown in FIG. **5**, the cooling chamber **30** is arranged directly in the focusing lens **22** surrounding housing portion **36** adjacent to the coil **33**. In both embodiments, the cooling chamber **30** extends mainly radially, i.e. its radial extension is at least approximately 50% greater than their axial extent. For example, the radial extent of the cooling chamber **30** to the radial extent of the coil **33** of the focusing lens **22** can be adjusted.

In the embodiments according to FIGS. **2**, **4** and **5**, the cooling chamber **30** is arranged adjacent to the coil **33** of the focusing lens **22**, as this is a main source of heat in the micro focus X-ray tube **11**. But embodiments of the invention are not limited to an arrangement of the cooling chamber **30** adjacent to the focusing lens **22**.

In the embodiments according to FIGS. **2** to **6**, the cooling chamber **30** has the form of an annular cylinder. The radial outer wall **45** and the radial inner wall **46** of the cooling chamber **30** are thus cylindrically shaped. The side walls **47** required for the formation of closed cooling chamber **30** are disk shape.

The cooling chamber **30** forming walls **45**, **46**, **47** comprise a material having a good thermal conductivity of at least 50 W/mK, in particular made of a material with a basis of aluminum, copper and/or brass.

As can be seen from the FIGS. **2**, **4** and **5**, the cross sectional area of the cooling chamber **30** in a longitudinal cross-section is more than ten times as large as the cross-sectional area of coolant lines **38** to be connected with the cooling chamber **30** via the connections **31**, **32**. The flow rate of the cooling medium in the cooling chamber **30** is more than ten times smaller than in the coolant lines **38** to be connected to cooling chamber **30** via the connections **31**, **32**. The clear internal dimensions of the cooling chamber **30** in a longitudinal cross-section is substantially greater than the wall thickness of the walls **45** to **47**, so that as much of the available space is used as a coolant flow. The aforementioned features contribute to the efficient cooling due to maximum cooling volume in the cooling chamber **30** at a given size.

Embodiments of the present invention are not limited to a coolant inlet **31**, a coolant outlet **32** and, optionally, a radial partition **48**. There are other embodiments conceivable having a plurality of coolant inlets **31**, a plurality of coolant outlets **32** and/or a plurality of radial partitions **48**.

The micro focus X-ray tube **11** may have a plurality of cooling chambers **30**, which may be, for example, axially offset from one another.

The cooling chamber **30** has been described above in connection with a micro focus X-ray tube **11** with an electron beam target **23**. The cooling chamber **30** may be used without further alternative easily into a micro focus X-ray tube **11** with a direct beam geometry, i.e. with reflective target.

The micro focus X-ray tube **11** has been described above for the preferred application in a CT apparatus. However, there are other applications conceivable for industrial X-ray inspection or x-ray measurement of components. In general, the micro focus X-ray tube **11** can be used in a high-resolution X-ray device having an imaging detector.

Due to the cooling of the micro focus X-ray tube **11** by means of the cooling medium flowing through the cooling chamber **30**, the thermally induced displacements of the focus position is counteracted. A feature here is that the cooling chamber **30** according to embodiments of the invention is essentially rotationally symmetric. Thereby, the substantially rotationally symmetrical temperature distribution in the micro focus X-ray tube **11**, which is mainly produced through rotationally symmetrical heat input, in particular due to the dissipation of energy in the electron optical system and the absorption of thermal energy over the surface of the tube housing **34**, is obtained upright, also when the micro focus X-ray tube **11** is not in thermal equilibrium. By the maintenance of the rotationally symmetrical temperature distribution in the micro focus X-ray tube **11**, lateral displacements of the focus, i.e. displacements in the direction perpendicular to the rotational axis arranged focal plane, can be suppressed very effectively. As these displacements in the focal plane have a large influence on the spatial resolution of the X-ray detector **12**, according to embodiments of the invention, significant increase the spatial resolution in the volume reconstruction can be achieved. A preheating of the micro focus

X-ray tube **11** and waiting for adjusting the thermal balance can be omitted, which reduces the total duration of measurement.

Due to the essentially rotationally symmetrical cooling, according to embodiments of the invention, essentially only axial thermal displacement of the focal point remains. These have a less damaging effect on the spatial resolution of the X-ray detector **12**. Furthermore, if necessary, the axial thermal displacements of the focal point by means of an increased cooling capacity, i.e. a properly designed cooling pump, can be effectively prevented.

Through the annular cooling chamber **30**, the embodiments of the invention is distinguished by a particular cooling line helically disposed about the axis of rotation, where in particular, deviations occur in the axial end regions by the rotational symmetry of the cooling.

In an embodiment, the cross-sectional area of the cooling chamber **30** is, at least five times in a longitudinal cross section, as large as the cross-sectional area of the coolant lines **38** to be connected to cooling chamber **30**. This feature contributes to a particularly efficient cooling because of the greatest possible cooling volume in the cooling chamber **30** for a given size. For the same reason, the clear internal dimensions of the cooling chamber **30** are greater in a longitudinal cross-section than the wall thickness of the cooling chamber **30**, so that as much of the available space is used as a coolant volume.

In an embodiment, the cooling chamber **30** is formed annularly cylindrical, wherein a radial inner wall **46** and a radial outer wall **45** of the cooling chamber **30** are shaped cylindrically. This form allows for efficient cooling because of a greatest possible volume of cooling at a given size, and is also advantageous in view of manufacturing technology.

In an embodiment, an inlet and an outlet for the cooling medium are arranged mutually offset in the circumferential direction of the tube, offset by at least approximately 90°. This arrangement can contribute to a possible uniform flow through the entire cooling chamber volume.

This written description uses examples to disclose the invention, including the preferred embodiments, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A micro focus X ray tube for a high resolution X-ray apparatus, the X-ray tube comprising: a housing having; an electron beam source for generating an electron beam; a focusing lens for focusing the electron beam; and a substantially rotationally symmetrical, ring-shaped cooling chamber positioned within the housing surrounding the focusing lens configured to circulate a liquid cooling medium.

2. The micro focus X-ray tube according to claim **1**, wherein a cross-sectional area of the cooling chamber in a longitudinal cross section is at least five times as large as a cross-sectional area of at least one coolant line, the coolant line connected to the cooling chamber.

3. The micro focus X-ray tube according to claim **1**, wherein the cooling chamber comprises an orifice and at least one wall and wherein an internal dimension of the cooling chamber orifice in a longitudinal cross-section is larger than a wall thickness of the at least one cooling chamber wall.

4. The micro focus X-ray tube according to claim **1**, wherein the cooling chamber comprises the shape of an annular cylinder.

5. The micro focus X-ray tube according to claim **1**, wherein the micro focus X-ray tube comprises an inlet and an outlet for the liquid cooling medium and wherein the inlet and the outlet in a circumferential direction of the cooling chamber are arranged offset to one another.

6. The micro focus X-ray tube according to claim **1**, wherein the micro focus X-ray tube comprises an inlet and an outlet for the liquid cooling medium and wherein the inlet and the outlet for the cooling medium are arranged opposite with respect to a tube axis.

7. The micro focus X-ray tube according to claim **1**, wherein the focusing lens comprises a coil and wherein the cooling chamber is arranged adjacent to the coil of the focusing lens.

8. The micro focus X-ray tube according to claim **1**, wherein the cooling chamber comprises a wall, the wall comprising a material having a thermal conductivity of at least 50 W/mK.

9. The micro focus X-ray tube according to claim **1**, wherein the cooling chamber comprises a wall, the wall comprises at least one of a material on the basis of aluminum, copper and brass.

10. A micro focus X-ray tube for a high resolution X-ray apparatus, the X-ray tube comprising: a housing having: an electron beam source for generating an electron beam; a focusing lens for focusing the electron beam; and a substantially rotationally symmetrical, ring-shaped cooling chamber surrounding the focusing lens, the cooling chamber including a cooling circuit and an inlet and an outlet connected to the cooling circuit.

11. The micro focus X-ray tube according to claim **10**, wherein the cooling circuit includes a pump.

* * * * *